Different soccer stud configurations effect on running and cutting movements

Sun, Dong; Gu, Yaodong; Mei, Qichang; Baker, Julien S.

Published in:
International Journal of Biomedical Engineering and Technology

DOI:
10.1504/IJBET.2017.083814

E-pub ahead of print: 24/04/2017

Document Version
Peer reviewed version

Different Soccer Stud Configurations Effect on Running and Cutting Movements

Abstract: The purpose of this study was to testing for difference in performance and injury risks between three different outsole configuration soccer shoes on natural turf. A total of 14 experienced soccer players participated in the tests. Participants were asked to complete tasks of straight-ahead running and 45° left sidestep cutting respectively at the speed of 5.0±0.2m/s on natural turf. They selected soccer shoes with firm ground design (FG), artificial ground design (AG) and turf cleats (TF) randomly. During 45° cut, FG showed significantly smaller peak knee flexion and greater abduction angles than TF. FG showed significant greater Peak horizontal ground reaction force (GRF) and average required traction ratio compared with AG and TF. This study also found that FG showed the highest peak pressure and force-time integral in the heel (H) and medial forefoot (MFF). FG may offer a performance benefit on artificial turf compared to AG and TF on natural turf. However, increased knee valgus angle and decreased knee flexion angle of FG may increase knee loading and risk of anterior cruciate ligament (ACL) injury. Higher vertical average loading rate and excessive plantar pressure of FG may also resulted in calluses observed in plantar skin, forefoot pain or even metatarsal stress fracture. In summary, FG would enhance athletic performance on natural turf, but also may undertake higher risks of non-contact injuries compared with AG and TF.

Keywords: stud configurations; running; cutting; natural turf.

1 Introduction

Soccer is one of the world's most popular sports and is enjoyed by many through playing at all levels. The biomechanical factors relevant to success in the game of soccer are those which relate to the technical performance of skills, to the equipment used and to the causative mechanisms of injury (Lees and Nolan, 1998). Soccer is a highly competitive contact sport, changes of speed and direction occur every 4–6 s in soccer, such as cutting and turning movements. During changes of direction the pivot leg initially decelerates the body, torso or pelvis then rotates away from the pivot leg towards the new direction (Sterzing et al., 2009). The ability to perform fast cutting maneuvers is essential in soccer. These cutting maneuvers are characterized by substantial changes in speed, thus requiring large horizontal impulses exerted by the feet on the surface (Luo and Stefanyshyn, 2011). These movements should be finished in a short time, and the quality of these movements not only influence athletic performance but also affect potential non-contact injuries of lower limbs (Driscoll et al., 2012; Smith et al., 2004).

During athletic movements, shoes are considered to play a vital role in the transmission of forces from surface to athlete, soccer players greatly rely on the design of their footwear to enable optimum performance (Hennig 2011). The soccer shoes provides grip to the playing surface, protects the foot, and facilitates ball control. To ensure a player can successfully perform the movement with minimal slipping, sufficient traction at the shoe-surface interface is required (Kent et al., 2015; Lake 2000). Previous study has highlighted traction between shoes and surface as a leading cause of ankle and knee injuries in soccer (Nigg and Segesser, 1988; Torg and Quedenfeld, 1971). Non-contact sports injuries often occurs in knee, ankle and foot, current studies had shown that these injuries closely related to the design of soccer shoes and turf conditions (Kaila 2007). Previous studies had shown that stud type, stud length, and stud geometry on various surface conditions would influence running performance (Muller et al., 2009). In the process of sidestep cutting movement, longer studs would provide more grip to improve athletic performance, but higher traction may lead to knee abduction moment significantly increased, which will increase the risk of ACL injury. Some studies had suggested an increased risk of ACL injury with decreased knee flexion angles and increased knee abduction angles during movements involving rapid changes of direction (Boden et al., 2000; Malinzak et al., 2001; Hewett et al., 2005). During running, some plantar regions could bear double or triple body weight, the additional pressure of these specific plantar regions may lead to potential risks of plantar fasciitis and metatarsal stress fractures (Morio et al., 2009). Pressure insoles was used to measure specific plantar anatomical regions of 21 professional soccer players, through the process of straight-ahead running and sidestep cutting, it was found that during sidestep cutting, plantar pressure of medial forefoot and lateral forefoot were significantly higher than straight-ahead running (Eils et al., 2004). It has been reported that artificial turf, including both infilled and non-infilled, contribute to 1.73 ACL injuries per 1000 athletes compared to 1.24 ACL injuries per 1000 athletes on natural turf (Dragoo et al., 2013). On the contrary, a recent three-year prospective study of 465 collegiate soccer players showed significantly lower injury incidence (46.6%) on artificial turf compared to natural turf (53.4%) (Meyers 2010). In addition, these studies had failed to find a significant difference in injury incidence between artificial turf and natural turf in soccer.

Several studies had revealed the effects of different soccer stud configurations on biomechanical characteristics on natural turf. Therefore, the purpose of this study was to investigate the lower limb kinematics and kinetics with different studded soccer shoes on natural turf during straight-ahead running and 45° left sidestep cutting movements. This could lead to a more comprehensive knowledge of player-surface interaction and provide further understanding of the mechanism of athletic performance and injury risk.

2 Materials and methods

2.1 Participants

The study was approved by the ethical committee of Ningbo University. Before the experiments, the subjects were informed of the objectives, requirements and experimental procedures. All gave informed written consent to participate in the study. Sixteen male soccer players (mean ± SD: age, 19.7 ± 1.2 y; height, 1.73 ± 0.04 m and body mass, 66.7 ± 4.4kg; soccer experience, 12.1 ± 2.2 y) from university soccer team were recruited for this study, and only right-leg dominant players were included in the study. A minimum of 2 years' experience with natural turf, free of major injuries to the lower extremities for the past 6 months.

2.2 Equipment

Different studded soccer shoes were sponsored by ANTA Sports Science Laboratory, stud design were firm ground design (FG) with 11 studs, artificial ground design (AG) with 23 studs, turf cleats shoes (TF) with 71 short cleats covering the entire sole (Table 1). Natural turf in this study was approved for national competition, a separate piece of natural turf was securely mounted on top of the force platform, the pile height was 60mm and weight of the natural turf ($25 kg \cdot m^{-2}$) ensured stability.

Table 1. Parameters of Three Pairs of Soccer Shoes

			
Studs design	Firm Ground (FG)	Artificial Ground (AG)	Turf Cleats (TF)
Number of studs	11	23	71
Length of studs	12-16mm	8-12mm	3-7mm

The 8-camera Vicon motion analysis system (Oxford Metrics Ltd., Oxford, UK) was used to capture participant's lower limb kinematics at a frequency of 200 Hz. A standard reflective marker set was pasted to different positions of the lower limb and used to define joint centers and axes of rotation. Subjects were required to wear tight-fitting pants and 16 reflective markers (diameter: 14 mm) were attached with adhesive on the left and right lower limbs, respectively. The marker locations included: anterior-superior iliac spine, posterior-superior iliac spine, lateral mid-thigh, lateral knee, lateral mid-shank, lateral malleolus, second metatarsal head and calcaneus. The marked points on the second metatarsal head and calcaneus were placed on the corresponding anatomical. The in-shoe plantar pressure measurement system (Novel Pedar System, Germany) was used to measure the pressure and force exerted on the insole pressure sensors, which were divided into seven anatomical parts, including heel (H), medial foot (MF), medial forefoot (MFF), central forefoot (CFF), lateral forefoot (LFF), big toes (BT) and other toes (OT) (Figure 1). All the insoles for the experiment had been regulated with a pressure pump before each participant's experiment. All subjects ran with the right foot step onto the force plate (Kistler, Switzerland), which was fixed in 6-meter away from the starting line and utilized to collect the ground reaction force (GRF) at a frequency of 1000 Hz. Velocity of straight-ahead running (0°) and cutting (45°) movements were measured using Brower timing lights (Brower Timing System, Draper, UT, USA). To ensure accurate kinetic data collection, a separate piece of natural turf was cut to 60 cm×90 cm to fit the dimension of force platform.

Figure 1 Anatomical areas of plantar in this study

2.3 *Data acquisition*

All running tests and experiments were conducted at the Sports Biomechanics Laboratory of Ningbo University. The design of experiment protocol is given in figure 2. A 3-minutes warm-up before experiment for every subject, shoe order and movements were randomized across subjects. Both straight-ahead running and 45° cut were performed at the speed of 5.0±0.2m/s, subjects were given one minute rests between trials and five minutes rests between shoe and movement conditions. If the subject did not land with right foot on the force platform, trails were discarded and the subject was asked to repeat the movement. Subjects were asked to land near the center of force platform to ensure accurate force collection. Subjects were instructed to heel landing of cutting movement, and landing pattern of straight-ahead running make no demands. Six trails that were deemed acceptable were collected in each condition. Kinematics and kinetics of each shoe and movement were synchronously measured.

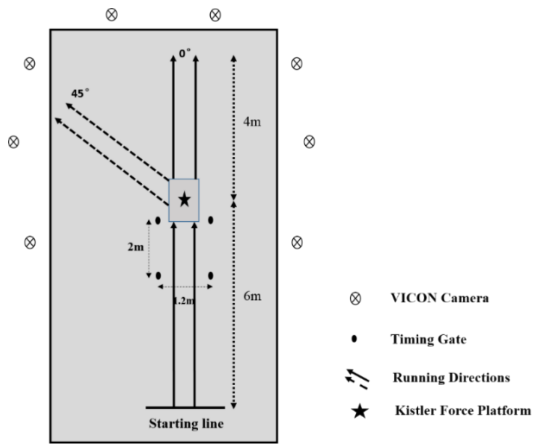

Figure 2 Design of experiment protocol

2.4 Statistical analysis

The SPSS 17.0 software (SPSS Inc., Chicago, IL, USA) was used for statistical analysis. The Post Hoc Multiple Comparisons and LSD (least significance difference) of ANOVA (analysis of variance) were taken for kinematic parameters, variables of ground reaction force, peak pressure and force time integral of the straight-ahead running and 45° left sidestep cutting .The significance level was set at 0.05.

3 Result

3.1 Kinematic results

Three dimensional kinematics of knee and ankle joints were analyzed during stance phase of 45° cut (Table 2 and 3). Kinematics of knee and ankle joints varies due to different stud configurations. In sagittal plane, peak knee flexion angle of firm ground design (FG) and artificial ground design (AG) were significantly smaller ($P<0.001$) than turf cleats (TF). Also knee flexion-extension range of motion (ROM) varied due to shoe conditions with FG generating smaller values ($p=0.013<0.05$) than TF (Table 2). In frontal plane, peak knee abduction angles of FG was significantly greater than AG ($p<0.001$) and TF ($p<0.001$). Peak ankle dorsiflexion angle showed no significant difference between stud conditions, but ankle dorsiflexion-plantarflexion range of motion (ROM) showed a significant difference ($p<0.001$) between FG and TF (Table 3).

Table 2. Summary of the knee kinematic variable of cutting movement, mean (*SD*)

	45°left sidestep cutting		
	FG	AG	TF
Peak flexion angle (°)	$38.8\pm5.2^{\#}$	$39.4\pm5.9^{*}$	42.9±6.1
Flexion-Extension ROM (°)	$27.6\pm3.3^{\#}$	28.7±4.3	29.8±3.7
Peak abduction angle (°)	$7.8\pm2.6^{\&,\#}$	-6.4±3.1	-6.3±3.4
Abduction-Adduction ROM (°)	4.4±1.5	3.2±1.3	3.2±1.1
Peak external rotation angle (°)	-8.7±2.9	-8.7±2.3	-8.6±3.5
Internal-External rotation ROM (°)	14.3±4.2	14.1±4.4	14.5±3.8

Notes: ROM represent range of motion. & indicates significant difference between FG and AG, $p<0.05$; # indicates significant difference between FG and TF, $p<0.05$; * indicates significant difference between AG and TF, $p<0.05$.

Table 3. Summary of the ankle kinematic variable of cutting movement, mean (SD).

	45°left sidestep cutting		
	FG	AG	TF
Peak dorsiflexion angle (°)	28.8±3.1	28.9±3.6	29.2±3.4
Dorsiflexion-Plantarflexion ROM (°)	51.7±7.4#	52.9±6.7	54.3±7.1
Peak inversion angle (°)	3.4±2.8	3.5±2.9	3.6±3.1
Inversion-Eversion ROM (°)	8.3±5.3	8.9±4.7	8.7±5.1
Peak internal rotation angle (°)	4.5±2.1	4.5±2.5	4.4±2.6
Internal-External rotation ROM (°)	13.7±4.3	13.9±3.8	13.8±4.4

Note: # indicates significant difference between FG and TF, $p<0.05$.

3.2 Kinetic results

Subjects were instructed wearing FG, AG and TF shoes to complete the tasks of straight running and 45°sidestep cutting respectively, with right foot land near the center of Kistler force platform to obtain ground reaction force (GRF). GRF of each subject were normalized to body weight (BW), peak vertical ground reaction force (vGRF) showed no significant different between different stud configurations. Horizontal ground reaction forces (hGRF) were calculated in this study, peak hGRF of FG was significantly higher than AG ($p<0.001$) and TF ($p<0.001$) during stance phase of 45° cut, separately. Vertical average loading rate (VALR) is the first peak GRF divided by the corresponding time (Force/Time). VALR of FG ($p<0.001$) and AG ($p=0.003<0.05$) were significantly higher than TF (Table 4), respectively.

Table 4. Variables of ground reaction force (n=14), mean (SD)

	straight running (0°)			45° sidestep cutting		
	FG	AG	TF	FG	AG	TF
Peak vertical ground reaction force (BW)	2.53 (0.12)	2.52 (0.14)	2.52 (0.17)	2.71 (0.23)	2.69 (0.19)	2.70 (0.25)
Peak horizontal ground reaction force (BW)	2.63 (0.22)	2.62 (0.19)	2.62 (0.24)	5.26 (0.48)[& #]	5.14 (0.47)	5.12 (0.51)
Vertical average loading rate (BW/s)	-	-	-	94.5 (7.1)[&]	94.4 (5.8)[*]	90.3 (6.7)
Time of contact (s)	0.165 (0.012)	0.166 (0.009)	0.165 (0.010)	0.207 (0.012)	0.208 (0.011)	0.208 (0.014)

Notes: "-" Not applicable for the given movement; BW, body weight;

& indicates significant difference between FG and AG, p<0.05;

# indicates significant difference between FG and TF, p<0.05;

* indicates significant difference between AG and TF, p<0.05.

The required (or utilized) traction was quantified using the time dependent traction ratio, dividing the horizontal by the vertical component of the ground reaction force. Horizontal ground reaction force (hGRF) was the resultant force in horizontal plane. Defining δ as required traction ratio between shoe and surface of cutting movement, the equation of traction ratio presents as follows:

$$\delta = hGRF/vGRF$$

The traction ratio shows large variability at initial and end of stance phase during cutting movement. Therefore, the average traction value was calculated in the interval where the traction ratio is rather constant, starting at 10% of stance phase and ending when the vertical ground reaction force dropped under body weight towards the end of stance phase (Clercq et al., 2014), as shown in the gray area of figure 3. The average required traction ratio of FG, AG and TF shoes were 2.18±0.12, 1.98±0.09 and 1.96±0.13. FG showed significant greater average required traction ratio compared with AG (p<0.001) and TF (p<0.001) during stance phase of 45° left sidestep cutting.

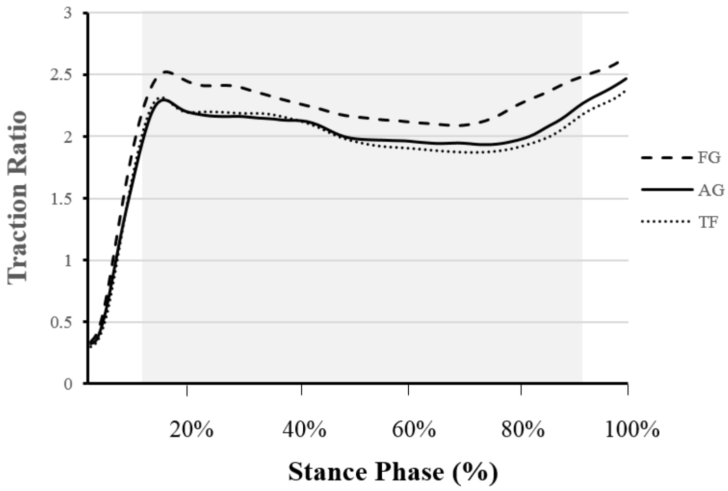

Figure 3 Traction ratio of three stud conditions during stance phase of 45° cut.

Note: The grey area indicates the interval during which the mean traction was calculated.

Peak pressure and force time integral were collected at different anatomical regions for the analysis of impact on different outsole hardness. Due to different foot strike patterns of straight-ahead running, the comparative analysis of different shoe type were only performed on the forefoot and toes. During stance phase of straight-ahead running, peak pressure in medial forefoot (MFF) of FG were significantly higher (P=0.008<0.05) than TF, and force-time integral in MFF of FG was also showed significantly higher (p=0.006<0.05) than TF (Figure 4).

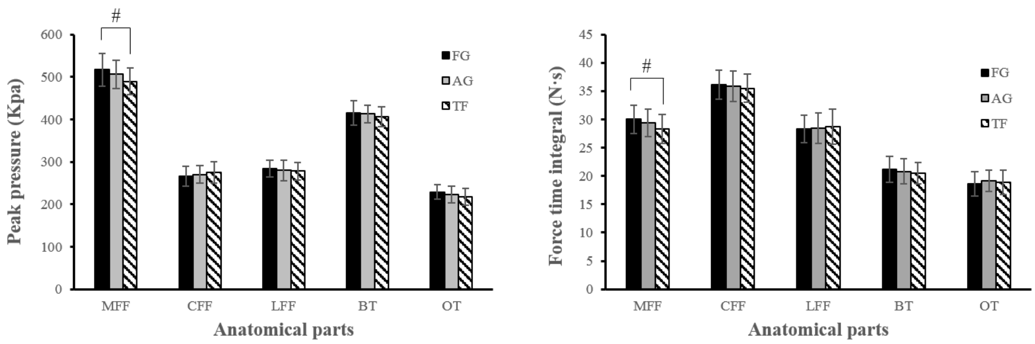

Figure 4 Peak pressure and force-time integral of three stud conditions in straight-ahead running.

Note: # indicates significant difference between FG and TF, p<0.05.

During stance phase of 45° left sidestep cutting, plantar pressure showed significant difference between different stud conditions in the heel (H) and medial forefoot (MFF) regions. Peak pressure of TF in the heel region was significantly smaller than AG

(P=0.004<0.05) and FG (p<0.001), and force-time integral of TF was also significantly smaller than AG (p=0.006<0.05) and FG (p=0.003<0.05). In the medial forefoot region, peak pressure of FG was significantly greater (p=0.009<0.05) than TF, and force-time integral of FG was also higher (p<0.001) than TF (see Figure 5).

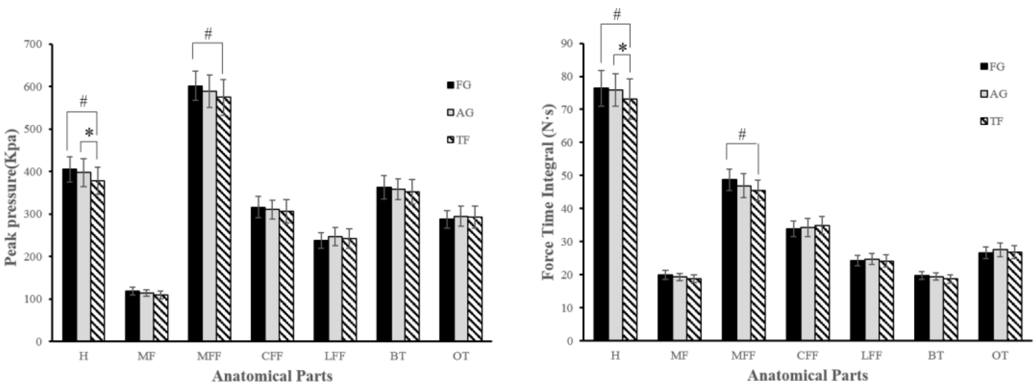

Figure 5 Peak pressure and force-time integral of three stud conditions in 45° cut.

Notes: # indicates significant difference between FG and TF, p<0.05;

* indicates significant difference between AG and TF, p<0.05.

4 Discussion

Experienced soccer players executed straight-ahead running and 45° left sidestep cutting movements, testing for difference in performance and non-contact injury risks with three soccer stud configurations on natural turf.

It was hypothesized that the natural turf studs would produce a greater peak vertical GRF and its loading rate compared to artificial turf studs and turf cleats during cutting movements. The results showed no significant differences in peak vertical GRF between stud type conditions of cutting movement. Gehring et al. (2007) found no significant differences in peak vertical GRF during a cross-over cutting performed by soccer players wearing traditional round studs and bladed studs, also Griffin et al. (2000) found that both soccer shoe stud conditions and outsole material showed no significant difference in peak vertical GRF. But peak horizontal GRF varies between different stud configurations during cutting movement in this study, FG produce a greater peak horizontal GRF compared with AG and TF. The utilized traction ratio of cutting movement in this study was dividing the horizontal by the vertical component of the ground reaction force (Luo and Stefanyshyn, 2011; Clercq et al., 2014), higher horizontal GRF of FG may produce more traction between shoe and surface. Sufficient traction between footwear and turf is extremely important for sport performance. It allows an athlete to cutting or turning sharply without skidding (Schrier et al., 2014). The grey area of figure 4 indicates the interval during which the mean traction ratio was calculated, mean utilized traction ratio of FG was significantly higher than AG and TF. It was found that cleat or stud shape and length as well as their arrangement across the outsole will modify the interaction of the shoe with the ground and produce different traction properties (Muller 2010). And the present study found as cleat length increased from 0% to 50% to 100% of its original length, straight accelerating and cutting performance improved with longer cleats (Muller 2009). Luo identified the more traction available, the more an athlete can lean into the surface and direct the GRF toward the favored direction, resulting in a greater acceleration (Luo and Stefanyshyn, 2011). However, Muller evaluate the traction characteristics of four different stud configurations on third-generation artificial turf, results showed mechanical traction ratio of soft ground design was the highest, but it displayed the worst results in the performance and in the perception testing among the four traction conditions (Muller 2010). In general, faster cutting should result in increased utilized traction.

During stance phase of straight-ahead running and 45° cut, peak pressure and force-time integral showed significant differences, mainly in the MFF. FG showed the highest peak pressure and force-time integral in MFF of both movements in this study. Compared with turf cleats shoes, natural stud design with longer stud may elevate plantar pressure of some areas on both third-generation turf and natural turf. Impulse is defined as force and time integral, Time of contact in straight-ahead running and 45° cutting showed no significant different between three stud conditions. The force produced an accumulative effect during a certain period of time for plantar regions, higher force-time integral could provide more impulse. Higher pressure also could provide more vertical propulsive force to achieve better athletic performance (Bergstra et al., 2014). In summary, speculated that FG may do more help to increasing athletic performance in both running and cutting movements.

Dynamic changes of direction have been determined as a risk factor for non-contact injuries in soccer, and these injuries normally occurred in ankle joint, knee joint and some plantar regions (Fong et al., 2007). During stance phase of cutting, FG and AG showed significant smaller knee flexion angles compared with TF. Decreased knee flexion angles reduce the ability of lower extremity to absorb compressive loads placed on the knee, putting it at risk for injury, increased knee flexion may reduce impact and load on knee joint (Boden et al., 2000; Derrick 2002), speculated smaller knee load of TF during cutting movement. Boden et al. (2000) also found that while the mechanism of frontal plane loading during landing and cutting tasks was different, increased knee valgus load during cutting was considered a risk factor for non-contact ACL injury. Peak knee abduction angles of FG was higher than TF, some studies had suggested an increased risk of ACL injury with decreased knee flexion angles and increased knee abduction angles during movements involving rapid changes of direction (McLean et al., 2004). Ankle kinematics did not display significant differences in peak dorsiflexion angle between stud conditions, but dorsiflexion-plantarflexion ROM was significantly greater for the TF compared with FG. Decreased ROM may lead to decreased absorption capacity of the ankle and increased injury potential. Malliaras et al. (2006) stated that the decreased dorsiflexion-plantarflexion ROM may reduce impact attenuation capacity of the ankle and therefore increase the knee joint loads and anterior tibia translation and strain on the ACL.

This study showed that FG was associated with the greatest peak horizontal GRF and VALR compared with TF. GRF and VALR have both been reported as risk factors associated with lower extremity injuries. Increased horizontal GRF make greater higher loads on the lateral ankle ligaments during 45° cut, leading to more potential risk to lateral ankle sprains (Jenkyn and Nicol, 2001). Higher VALR may increase the impact force to lower limbs and may lead to potential risk of tibia stress fracture and plantar fasciitis (Mei et al., 2015). Peak pressure and force-time integral in the heel (H) region of FG were also significantly higher than TF (Figure 5), which would also increase the potential risk factors of tibia stress fractures and plantar fasciitis (Lieberman et al., 2010). Speculated TF may provide more impact absorption compared with FG. Higher utilized traction could produce more grip which allows athletes to cutting and turning rapidly without skidding. However, the shortcoming of higher utilized traction of FG has also been proposed to be associated with athlete injury. It has been proposed that higher utilized traction might lead to risk of slip resistance and foot fixation which might increase the load of lower limbs. Slip resistance and foot fixation are two potential factors of non-contact injuries. Foot fixation has been related to the knee injuries (D'Ambrosia 1985; Torg 1982). In the direction phase of cutting movement, to prevent slipping injuries an adequate level of traction ratio is necessary, speculated that traction ratio should be as low as possible and able to provide adequate slip resistance.

FG showed significant greater peak pressure and force-time integral compared with TF in the MFF, also greater than AG but showed no significant difference. The medial forefoot (first and second metatarsal) of FG bears more loading compared with other stud conditions during stance phase of cutting movement. Though increased plantar pressure is correlated with faster running speed, excessive pressure and an accumulative effect in a small area may result in calluses observed in plantar skin, forefoot pain or even metatarsal stress fracture (Grouios 2004; Keijsers et al., 2013). Which is consistent with studies that higher forefoot pressure of bladed cleat design could concluded to be substantially more harmful than round cleat design (Bentley et al., 2011). During stance phase of 45° cut, increased plantar pressure of FG elevate the compressive load on the knee joint which may be connect with increased risk of ACL injury, in addition to decreased knee flexion angle and increased knee abduction angle.

5 Conclusion

During stance phase of 45° cut， decreased knee flexion angles and increased knee abduction angles of firm ground design (FG) may increase knee loading and risk of anterior cruciate ligament (ACL) injury. Higher utilized traction of FG could produce more grip which allows athletes to cutting rapidly without skidding. However, higher utilized traction might lead to risk of slip resistance and foot fixation which might increase the load of lower limbs. Elevated plantar pressure of FG may improve impulsive force to enhance athletic performance, therefore excessive pressure and an accumulative effect in a small area may result in calluses observed in plantar skin, forefoot pain or even metatarsal stress fracture. In summary, FG may enhance athletic performance on natural turf, but also may undertake higher risks of non-contact injuries compared with artificial ground design (AG) and turf cleats (TF).

Acknowledgement: The study sponsored by National Natural Science Foundation of China (81301600), K.C.Wong Magna Fund in Ningbo University, and Zhejiang Xinmiao Innovation Talents Scheme (2015R405094).

References

Bentley, J. A., Ramanathan, A. K., Arnold, G. P., Wang, W., & Abboud, R. J. (2011). Harmful cleats of football boots: 'A biomechanical evaluation', *Foot and Ankle Surgery*, Vol. 17, No. 3, pp. 140-144.

Bergstra, S. A., Kluitenberg, B., Dekker, R., Bredeweg, S. W., Postema, K., Van den Heuvel, E. R., ... & Sobhani, S. (2014). 'Running with a minimalist shoe increases plantar pressure in the forefoot region of healthy female runners', *Journal of Science and Medicine in Sport*, Vol. 18, No. 4, pp. 463-468.

Boden, B. P., Feagin Jr, J. A., & Garrett Jr, W. E. (2000). 'Mechanisms of anterior cruciate ligament injury', *Orthopedics*, Vol. 23, No. 6, pp. 573-578.

D'Ambrosia, R. D. (1985). 'Orthotic devices in running injuries', *Clinics in sports medicine*, Vol. 4, No. 4, pp. 611-618.

De Clercq, D., Debuyck, G., Gerlo, J., Rambour, S., Segers, V., & Van Caekenberghe, I. (2014). 'Cutting performance wearing different studded soccer shoes on dry and wet artificial turf', *Footwear Science*, Vol. 6, No. 2, pp. 81-87.

Derrick, T. R., Dereu, D. A. R. R. I. N., & McLean, S. P. (2002). 'Impacts and kinematic adjustments during an exhaustive run', *Medicine and science in sports and exercise*, Vol. 34, No. 6, pp. 998-1002.

Dragoo, J. L., Braun, H. J., & Harris, A. H. (2013). 'The effect of playing surface on the incidence of ACL injuries in National Collegiate Athletic Association American Football', *The Knee*, Vol. 20, No. 3, pp. 191-195.

Driscoll, H., Kirk, B., Koerger, H., & Haake, S. (2012). 'Influence of outsole design on centre of rotation during turning movements', *Procedia Engineering*, Vol. 34, pp. 301-306.

Eils, E., Streyl, M., Linnenbecker, S., Thorwesten, L., Völker, K., & Rosenbaum, D. (2004). 'Characteristic plantar pressure distribution patterns during soccer-specific movements', *The American Journal of Sports Medicine*, Vol. 32, No. 1, pp. 140-145.

Fong, D. T. P., Hong, Y., Chan, L. K., Yung, P. S. H., & Chan, K. M. (2007). 'A systematic review on ankle injury and ankle sprain in sports', *Sports medicine*, Vol. 37, No. 1, pp. 73-94.

Gehring, D., Rott, F., Stapelfeldt, B., & Gollhofer, A. (2007). 'Effect of soccer shoe cleats on knee joint loads', *International journal of sports medicine*, Vol. 28, No. 12, pp. 1030-1034.

Griffin, L. Y., Agel, J., Albohm, M. J., Arendt, E. A., Dick, R. W., Garrett, W. E., ... & Johnson, R. J. (2000). ‘Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies’, *Journal of the American Academy of Orthopaedic Surgeons*, Vol. 8, No. 3, pp. 141-150.

Grouios, G. (2004). ‘Corns and calluses in athletes’ feet: a cause for concern’, *The Foot*, Vol. 14, No. 4, pp. 175-184.

Hennig, E. M. (2011). ‘The influence of soccer shoe design on player performance and injuries’, *Research in Sports Medicine*, Vol. 19, No. 3, pp. 186-201.

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., ... & Succop, P. (2005). ‘Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes a prospective study’, *The American journal of sports medicine*, Vol. 33, No. 4, pp. 492-501.

Jenkyn, T. R., & Nicol, A. C. (2001). ‘Protective ankle muscle activation strategies during quick cutting movement in humans’, *In 25th annual meeting of American Society of Biomechanics, San Diego, CA*.

Kaila, R. (2007). ‘Influence of modern studded and bladed soccer boots and sidestep cutting on knee loading during match play conditions’, *The American journal of sports medicine*, Vol. 35, No. 9, pp. 1528-1536.

Kent, R., Forman, J. L., Crandall, J., & Lessley, D. (2015). ‘The mechanical interactions between an American football cleat and playing surfaces in-situ at loads and rates generated by elite athletes: a comparison of playing surfaces’, *Sports biomechanics*, Vol. 14, No. 1, pp. 1-17.

Keijsers, N. L. W., Stolwijk, N. M., Louwerens, J. W. K., & Duysens, J. (2013). ‘Classification of forefoot pain based on plantar pressure measurements’, *Clinical biomechanics*, Vol. 28, No. 3, pp. 350-356.

Lake, M. J. (2000). ‘Determining the protective function of sports footwear’, *Ergonomics*, Vol. 43, No. 10, pp. 1610-1621.

Lees, A., & Nolan, L. (1998). ‘The biomechanics of soccer: a review’, *Journal of sports sciences*, Vol. 16, No. 3, pp. 211-234.

Lieberman, D. E., Venkadesan, M., Werbel, W. A., Daoud, A. I., D’Andrea, S., Davis, I. S., ... & Pitsiladis, Y. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*, Vol. 463, No. 7280, pp. 531-535.

Luo, G., & Stefanyshyn, D. (2011). ‘Identification of critical traction values for maximum athletic performance', *Footwear Science*, Vol. 3, No. 3, pp. 127-138.

Malinzak, R. A., Colby, S. M., Kirkendall, D. T., Yu, B., & Garrett, W. E. (2001). 'A comparison of knee joint motion patterns between men and women in selected athletic tasks', *Clinical Biomechanics*, Vol. 16, No. 5, pp. 438-445.

Malliaras, P., Cook, J. L., & Kent, P. (2006). 'Reduced ankle dorsiflexion range may increase the risk of patellar tendon injury among volleyball players', *Journal of science and medicine in sport*, Vol. 9, No. 4, pp. 304-309.

McLean, S. G., Lipfert, S. W., & van den Bogert, A. J. (2004). 'Effect of gender and defensive opponent on the biomechanics of sidestep cutting', *Medicine and Science in Sports and Exercise*, Vol. 36, No. 6, pp. 1008-1016.

Mei, Q., Fernandez, J., Fu, W., Feng, N., & Gu, Y. (2015). 'A comparative biomechanical analysis of habitually unshod and shod runners based on a foot morphological difference', *Human movement science*, Vol. 42, pp. 38-53.

Meyers, M. C. (2010). 'Incidence, mechanisms, and severity of game-related college football injuries on fieldturf versus natural grass a 3-year prospective study', *The American journal of sports medicine*, Vol. 38, No. 4, pp. 687-697.

Morio, C., Lake, M. J., Gueguen, N., Rao, G., & Baly, L. (2009). 'The influence of footwear on foot motion during walking and running', *Journal of biomechanics*, Vol. 42, No. 13, pp. 2081-2088.

Müller, C., Sterzing, T., Lange, J., & Milani, T. L. (2010). 'Comprehensive evaluation of player-surface interaction on artificial soccer turf', *Sports Biomechanics*, Vol. 9, No. 3, pp. 193-205.

Müller, C., Sterzing, T., & Milani, T. (2009). 'Stud length and stud geometry of soccer boots influence running performance on third generation artificial turf', In *ISBS-Conference Proceedings Archive*, Vol. 1, No. 1.

Nigg, B. M., & Segesser, B. (1988). 'The influence of playing surfaces on the load on the locomotor system and on football and tennis injuries', *Sports Medicine*, Vol. 5, No. 6, pp. 375-385.

Schrier, N. M., Wannop, J. W., Lewinson, R. T., Worobets, J., & Stefanyshyn, D. (2014). 'Shoe traction and surface compliance affect performance of soccer-related movements', *Footwear Science*, Vol. 6, No. 2, pp. 69-80.

Smith, N., Dyson, R., & Janaway, L. (2004). 'Ground reaction force measures when running in soccer boots and soccer training shoes on a natural turf surface', *Sports Engineering*, Vol. 7, No. 3, pp. 159-167.

Sterzing, T., Müller, C., Hennig, E. M., & Milani, T. L. (2009). ‘Actual and perceived running performance in soccer shoes: A series of eight studies’, *Footwear Science*, Vol. 1, No. 1, pp. 5-17.

Torg, J. S. (1982). ‘Athletic footwear and orthotic appliances’, *Clinics in sports medicine*, Vol. 1, No. 1, pp. 157-175.

Torg, J. S., & Quedenfeld, T. (1971). ‘Effect of shoe type and cleat length on incidence and severity of knee injuries among high school football players’, *Research Quarterly. American Association for Health, Physical Education and Recreation*, Vol. 42, No. 2, pp. 203-211.